An Exploratory Expert-Study for Multi-Type Haptic Feedback for Automotive Virtual Reality Tasks

Alexander Achberger, Patrick Gebhardt, and Michael Sedlmair

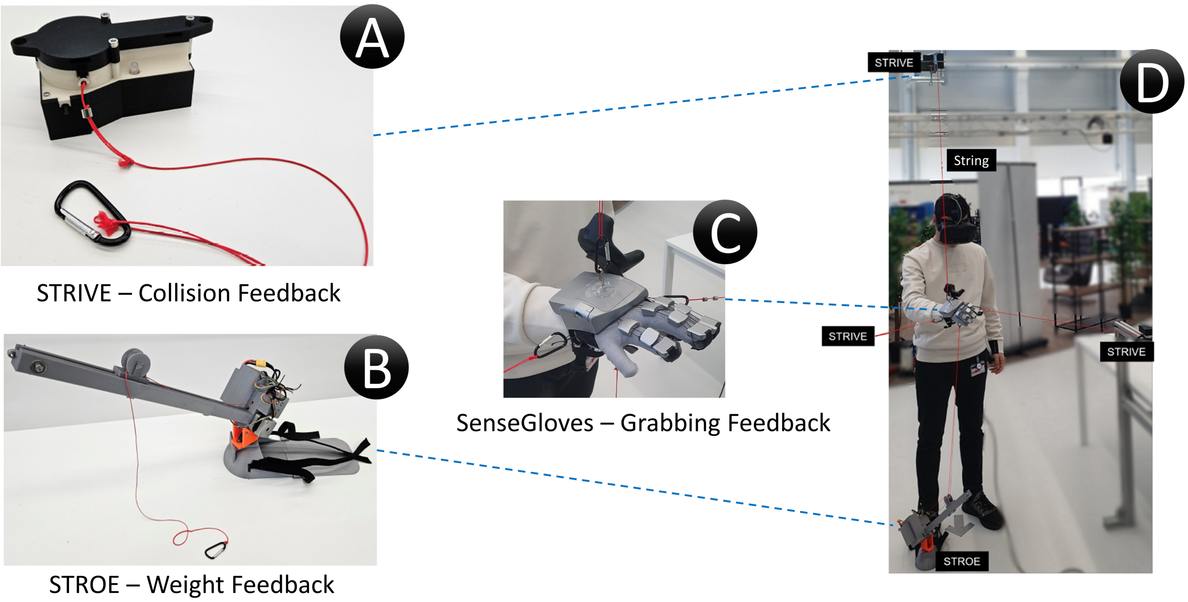

Fig. 1: Our multi type-haptic feedback system, combining three haptic feedback devices: (A) STRIVE [3], a string-based device to simulate collisions with the user's hand; (B) STROE [2], another string-based device for weight simulation; (C) SenseGlove to simulate grabbing feedback; (D) the multi-type haptic feedback system that combines all three haptic devices.

Abstract—Previous research has shown that integrating haptic feedback can improve immersion and realism in automotive VR applications. However, current haptic feedback approaches primarily focus on a single feedback type. This means users must switch between devices to experience haptic stimuli for different feedback types, such as grabbing, collision, or weight simulation. This restriction limits the ability to simulate haptics realistically for complex tasks such as maintenance. To address this issue, we evaluated existing feedback devices based on our requirements analysis to determine which devices are most suitable for simulating these three feedback types. Since no suitable haptic feedback system can simulate all three feedback types simultaneously, we evaluated which devices can be combined. Based on that, we devised a new multi-type haptic feedback system combining three haptic feedback devices. We evaluated the system with different feedback-type combinations through a qualitative expert study involving twelve automotive VR experts. The results showed that combining weight and collision feedback yielded the best and most realistic experience. The study also highlighted technical limitations in current grabbing devices. Our findings provide insights into the effectiveness of haptic device combinations and practical boundaries for automotive virtual reality tasks.

Index Terms—Haptics, Virtual Reality, Human Computer Interaction

1 INTRODUCTION

Virtual reality (VR) is becoming increasingly important in the automotive industry's development process [9, 47]. It helps engineers save money and enhance product quality by enabling virtual pre-construction studies. Current feedback systems in automotive VR mostly use visual and auditory feedback [9]. However, there's a growing interest in adding haptic feedback, allowing engineers to physically interact with virtual car parts. Studies indicate that integrating haptics into automotive VR can improve immersion, realism, and digital trust [3].

Currently, haptic engineers mainly use single-type haptic feedback devices, which has drawbacks. Firstly, users have to switch between different devices for various types of feedback, such as grabbing, collision, and weight simulation. Secondly, single-type devices are inadequate for complex VR tasks requiring simultaneous simulation of multiple haptic types. For instance, in maintenance tasks, where engineers assess the feasibility of replacing a car component, engineers need three types of feedback. They require realistic "grabbing" to securely hold components, sense "collisions" with the car to avoid scratches, and feel the "weight" of components for safe handling and a correct ergonomic pose evaluation.

Multi-type haptics offer a potential solution to this issue. A major challenge in developing such systems is managing spatial interference

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- *Alexander Achberger is with University of Stuttgart. E-mail: alexander.achberger@visus.uni-stuttgart.de*
- *Patrick Gebhardt is with University of Stuttgart. E-mail: pattigebhardt@gmx.de*
- *Michael Sedlmair is with University of Stuttgart. E-mail: michael.sedlmair@visus.uni-stuttgart.de*

Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx

among different actuators [42]. For instance, HaptX Inc. has introduced the HaptX Glove[1], which features numerous tactile actuators and provides force feedback. However, the glove is large and expensive, and it does not simulate sensations like temperature.

There are only a few haptic feedback devices available that support grabbing feedback combined with kinesthetic feedback for simulating forces on the hand. These include HIRO III [19], Flying phantoms [8], or CyberForce[2], which functions similarly but shares the same drawbacks. On one hand, they are expensive, complex, and can mostly cover only small workspaces, such as $30.5cm \times 30.5cm \times 51cm$ for CyberForce, which is insufficient for more complex automotive VR tasks. Additionally, their design does not allow for reducing complexity by decreasing the number of provided feedback types, such as using a simple controller instead of a grabbing device if grabbing is not essential in the current VR task.

To our knowledge, no haptic feedback device can simultaneously simulate weight, grabbing, and collision forces while also allowing the option to disable one feedback type to reduce complexity.

While individual devices have proven beneficial for simpler tasks, their effectiveness in more complex scenarios, like those in the automotive field, is still unclear. Our research aimed to investigate the pros and cons of combining existing devices into a multi-type haptic feedback system designed to integrate weight, grabbing, and collision forces. Our primary users are VR experts in the automotive industry, assessing car mechanics' performance in specific repair tasks. Haptic feedback in VR simulations is crucial for trust and identifying otherwise unnoticed issues. Little is known about multi-type haptic feedback in industrial VR use cases. We aimed to understand how device combinations could enhance experts' VR experience and design a setup that allows flexibility in disabling specific feedback types.

Combining all potential haptic feedback device configurations is mostly impossible and beyond the scope of this paper. Instead, we focus on integrating three types of haptic feedback, *collision*, *weight*, and *grabbing*, for an automotive VR task. We defined 11 requirements for haptic feedback devices tailored to the automotive VR task.

Subsequently, we evaluated 60 haptic feedback devices capable of covering these feedback types either individually or in combination. We then explored which devices could simulate all three feedback types simultaneously. After selecting the most suitable devices, we integrated them into a multi-type setup designed for flexibility, allowing the reduction of feedback types for simpler VR tasks to minimize complexity. Following a pilot study, we conducted an exploratory expert study with 12 automotive VR experts. This study focused on qualitative feedback and compared different setup combinations to identify practical boundaries and effective combinations and determine which setup offers the greatest benefit, with or without technical device limitations.

Results indicate that combining *weight* and *collision* feedback offers the most significant benefits. However, when assuming no technical limitations, about half of the participants rated *grabbing* as the most essential feedback type. This suggests that current technical limitations hinder the effectiveness of grabbing functionality. We also outline implications for future research on multi-type haptic feedback systems.

In summary, our research makes the following contributions:

- Investigation of suitable haptic feedback devices based on requirements we collected: We explored and determined which haptic feedback devices would be suitable for combined usage in automotive VR tasks.
- Multi-type haptic feedback system: We have combined three suitable haptic feedback devices so that they work simultaneously.
- Expert study: We conducted a user study with 12 automotive VR experts to evaluate the experience and benefits of different combinations of feedback types within our feedback system when applied to automotive VR tasks.

2 BACKGROUND AND RELATED WORK

We sought a definition of haptic feedback that covers various types like grabbing, collision, and weight sensation. While we found definitions for multimodal haptic feedback, which involve haptic sensations across different modalities [42], these definitions did not fully match our needs. Some focused on different gesture interactions, which only partially suited our requirements, especially for grabbing. Therefore, we chose to use the term "multi-type" which we define as a broader form of haptic feedback not limited to specific modalities or gestures, thus encompassing grabbing, collision, and weight simulation.

Wang et al. [42] identified the core challenge of providing various haptic stimuli within a limited space for actuators, a challenge that mirrors our own. Generating haptic stimuli requires the usage of actuators, such as motors, pneumatics, or voice coil actuators. However, a single type of actuator cannot produce diverse haptic stimuli. For example, voice coil actuators are incapable of exerting forces on a user.

To tackle this challenge, Park et al. [36] developed a haptic feedback device equipped with a vibration and impact actuator. This handheld device effectively simulates texture and impact feedback. The researchers evaluated the device by examining various types of material with the haptic device, using vibrotactile and impact feedback separately and in combination. The results revealed that participants perceived greater realism with single feedback types than combined ones for specific material types. These results provide motivation to design haptic feedback devices in a manner that allows them to flexibly decide which and how many types of feedback they wish to simulate.

Culbertson et al. [15] combined a vibrotactile actuator with the kinesthetic haptic feedback device Phantom Omni. They successfully simulated 15 distinct virtual surfaces based on the model components friction, tapping transient, and texture. Through a user study, they discovered that the importance of these three separate model components varied across the surfaces. Another approach, introduced by Al-Sada et al. [6], involves HapticSnakes. This snakelike robot offers taps, gestures, airflow, brushing, and gripper-based feedback on both the front and back of the body. The results of their user study demonstrated differing opinions regarding the most valuable haptic feedback, but there was a shared consensus on the robot's usefulness. Additionally, there are HIRO III [19], Flying Phantoms [8], and CyberForce, which are kinesthetic feedback devices that use a glove-like end-effector to interact with both the fingers and the entire arm, in contrast to the state-of-the-art predefined handle as an end-effector. However, these devices are costly and have high complexity, even when only one feedback type, such as weight simulation, is required.

Another way to foster sensations of grabbing and weight is to use tangible objects. To increase flexibility, some research has also investigated physical tangible objects that can modify their shape [14, 23] or weight [13, 29]. However, these abilities are limited as tangible objects can only slightly alter one property at a time. We have not found any tangible device capable of simulating both the shape of a screwdriver and a screw, as well as their weight, in a single object. Using multiple tangible objects (e.g., real objects) and tracking them could be an alternative solution. However, this approach might be time-consuming and expensive if the necessary objects are not readily available. Moreover, in the early stages of the development process, which we are focusing on, specific parts may not yet exist.

Prior research has shown that various feedback devices can simulate different haptic types across different body parts, each facing unique challenges. Unlike previous studies, our research doesn't focus on creating new haptic devices but aims to combine existing ones into a multi-type system. To our knowledge, no existing multi-type haptic feedback system covers collision simulation, grabbing feedback, and weight simulation while also simplifying to a single feedback type.

3 AUTOMOTIVE VR TASK REQUIREMENTS

To begin, we provide a description of the automotive VR tasks to gain insight into the necessity and application of *grabbing*, *weight*, and *collision* feedback. Afterward, we outline the requirements we have collected for the devices to simulate these three types of feedback effectively.

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[1] HaptX. Haptx Gloves. https://haptx.com/

[2] CyberGlove System Inc. CyberForce. https://www.cyberglovesystems.com/

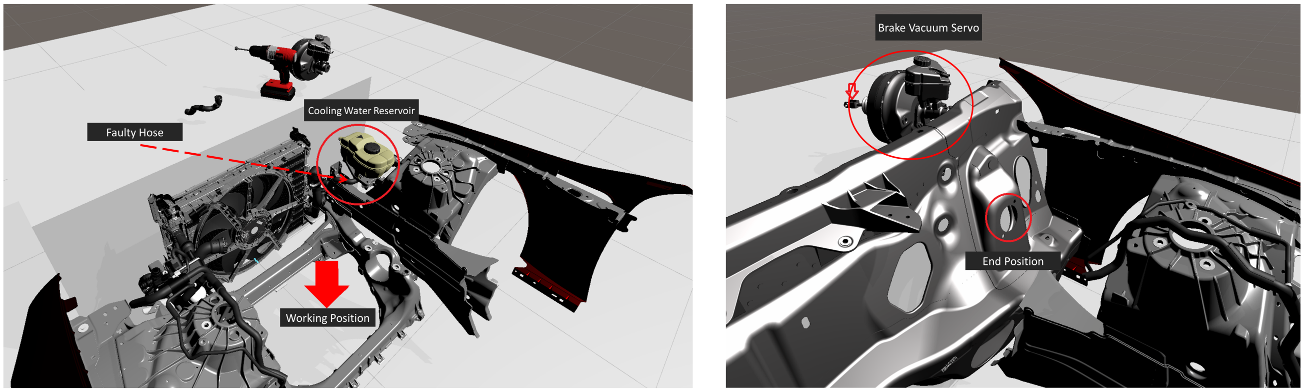

Fig. 2: Left: The first step of the automotive VR task involves replacing a faulty hose. Right: The second step requires placing the brake vacuum servo in the end position.

3.1 Automotive VR Task

For the tasks, we selected an automotive VR task that utilizes real automotive car data. The task involves replacement and packaging tasks, as depicted in Figure 2. In a broader context, the task falls under assembly and maintenance categories. Experts evaluate various aspects, including ergonomic posture, reachability, accessibility, and object fitting within target locations. Hence, the specific task can also be generalized to other automotive scenarios. We have chosen the task type because it encompasses diverse interactions with virtual objects.

The task began with replacing a faulty hose under the cooling water reservoir. It involved removing the reservoir, unscrewing and detaching the holder, replacing the hose, reattaching and screwing the holder, and then reinstalling the reservoir. All materials, including a power drill, were within reach on the table, minimizing the participants' need to move from their starting position.

Following completing the first step, a five-second break was provided before the scene was rotated by 180 degrees. The rotation was implemented to facilitate the second step on the opposite side of the engine compartment. This approach eliminated the requirement for users to rotate physically, which could hinder their experience with a haptic feedback system. The second step involved a single objective: placing the brake vacuum servo into the engine compartment and evaluating the available space for its placement.

3.2 Device Requirements

In the following, we list the requirements we collected in general and for each haptic type. We gathered our requirements by performing the described task ourselves, engaging in discussions with VR experts, or observing automotive VR experts while they conducted other VR tasks. By "VR experts", we refer to the persons who participated in our study and work within automotive companies, using VR in their work. Table 2 shows more information about the experts. All requirements are listed in Table 1 and explained in detail in the next subsections.

3.2.1 General Feedback Requirements

This subsection addresses all requirements that are not specific to only one feedback type. Since users should be able to execute realistic grabbing movements, they need to have freedom of finger movement. However, many haptic feedback devices come with predefined handles, like Thor's Hammer [25] or Virtuose 6D [22], which restrict finger movement and hinder the ability to grab realistically. Therefore, we define that the devices must not have **predefined handles** $RGen_{Handle}$.

Another general requirement is the **movement range** $RGen_{Mo-Range}$, which defines how much space the haptic feedback system should cover with haptic stimuli. As the task is primarily stationary and requires hand movements or body bending, we define the movement range based on the maximum object distances. Therefore, we define the movement range with $1m \times 1m \times 1m$.

3.2.2 Grabbing Feedback Requirements

The VR task requires to *grab* various objects, such as the cooling water reservoir, the brake vacuum servo, or the power drill. To evaluate whether there is sufficient space within the virtual environment for users to maneuver their hands comfortably during the grasping process, the user has to have realistic virtual finger poses. Therefore, one of the requirements for the grabbing feedback is the provision of **kinesthetic feedback** $RGrab_{Kines}$ to ensure accurate finger poses. Conversely, tactile feedback, which enables the perception of material properties of the grasped objects, is not necessary for our VR tasks.

Estimating the maximum **grab force** ($RGrab_{Force}$) is challenging due to variations in material friction and finger skin moisture. We based our estimate on research by Polygerino et al. [38], which found that a fingertip force of about 7.1 N is required for an object weighing 1.5 kg. Given that our heaviest object weighs around 4 kg and has a higher friction coefficient due to its metal composition, we estimate the **grab force** to be 15 N per finger.

Furthermore, our observations indicated that a **minimum of four fingers** $RGrab_{Fingers}$, including the thumb, needed to be involved in the grasping interactions. As a result, our focus lies solely on haptic feedback gloves that support a minimum of four fingers. Regarding other requirements, such as latency, we do not specify them closer, as most feedback devices for grabbing do not describe their latency.

3.2.3 Collision Feedback Requirements

Achberger et al. [3] showed that haptic collision simulation in automotive tasks improves workspace perception and increases confidence in task outcomes. Regarding our specific automotive task, we now clarify what we mean by *collision* feedback. Collision feedback involves halting the movement of our virtual hand or the object being held when a collision occurs with the virtual environment. To achieve this, we require a **kinesthetic** haptic feedback device capable of physically impeding hand movement. $RColl_{Kines}$

After evaluating our task's virtual environment, we have determined that three **degrees of freedom** $RColl_{DoF}$ are necessary to arrest our movement effectively. While simulating torque can be beneficial, it is not a mandatory requirement. Hence, our focus lies exclusively on kinesthetic feedback devices that offer at least three degrees of freedom.

Regarding latency, we measured the maximum hand velocity during the VR task, observing a peak velocity of 40 cm/s. As latency entails that the user will first halt after the latency period, potentially allowing for slight penetration into objects, we define latency by the maximum penetration permitted in this task. Following discussions with VR experts, we established the maximum penetration distance as 1 cm. Consequently, we calculated the **latency** $RColl_{Lat}$ to be 25 ms, based on the maximum hand velocity.

Devices	General Req.		Grabbing Req.			Collision Req.			Weight Req.		
Requirements	Handle	Mo-Range	Kines	Force	Fingers	Kines	DoF	Lat	Fo-Range	Prec	Lat
Values	True	>= $1m \times 1m \times 1m$	True	>= 1 N	>= 4	True	>= 3	<= 25 ms	<= 0.25 N & >= 40 N	<= 1 N	<= 500 ms
SenseGlove Nova	✓	Inf.	✓	20 N	4						
Dexmo	✓	Inf.	✓	0.5 Nm	5						
HaptX Gloves G1	✓	Inf.	✓	0.9 Nm	5						
STRIVE [3]	✓	$2m \times 2m \times 2m$				✓	3	30 ms			
STROE [2]	✓	Inf.				✓	1	250 ms	> 0.5 N & < 7.2 N	n.A.	250 ms
EMS [32]	✓	Inf.				✓	3	n.A.	n.A.	n.A.	n.A.
SPIDAR-W [34]	✓	Inf.				✓	3	n.A.	n.A.	n.A.	n.A.
PropellerHand [4]	✓	Inf.				✓	2	429 ms	> 0.17 N & < 11 N	0.03 N	429 ms
Wind-Blaster [28]	✓	Inf.				✓	1	n.A.	> n.A. & < 1.5 N	n.A.	429 ms
Drone [1]	✓	Inf.				✓	3	n.A.	> 0 N & < 3 N	n.A.	n.A.

Table 1: The defined requirements for the automotive VR tasks, as well as the devices for grabbing, collision, and weight feedback, and their fulfillment of these requirements.

3.2.4 Weight Feedback Requirements

Simulating the *weight* of objects is crucial for assessing task ergonomics. The weight directly affects task complexity and physical effort. *Weight* simulation refers to replicating the actual force on users' hands when they grasp a virtual object. We focus on force feedback that causes muscle fatigue, which is essential for evaluating the ergonomic implications in automotive tasks.

The **range of the weights** $RWeig_{Fo-Range}$, the device should be able to simulate is from about 25 g (0.25 N) with the lightest object, the screw, and about 4 kg (40 N) with the heaviest object, the brake vacuum servo. Therefore, devices that can only simulate weight shift, such as Transcalibur [40] or Shifty [45], are unsuitable for our use cases since they cannot simulate varying weights.

For the **precision** of the weight simulation ($RWeig_{Prec}$), referring to the weight step sizes it can simulate, the smallest difference in our use case is between a screw and a hose, which is 150 g. Thus, we set the precision requirement to 100 g (1 N).

Since lifting an object is a gradual process, we do not require low **latency** $RWeig_{Lat}$ of only a few milliseconds. In the event of colliding the grabbed object with the ground, the collision feedback device will counteract the force to halt the weight simulation. Thus, we have defined the latency to be around 500 ms. Unlike *collision* simulation, we only require force feedback in one degree of freedom, specifically directed downwards.

4 CHOICE OF HAPTIC FEEDBACK DEVICES

This section consists of three parts. First, we provide an overview of the devices we evaluated. Second, we explain our final choice for the haptic feedback devices we used for our multi-type haptic feedback system, based on our requirement. It is important to note that we only include haptic feedback devices that are either commercially available or can be replicated. By replication, we mean sufficient information is available to reproduce the device accurately. Third, we report insights we gained during our device analysis.

4.1 Device Evaluation

Our first step was to find devices for grabbing, colliding, and weight simulation and evaluate whether they meet our specified requirements. Due to our specific requirements, we focused solely on kinesthetic feedback devices. We conducted a semi-structured literature review to search for haptic feedback devices. During this process, we discovered literature reviews that covered multiple haptic feedback devices, and additionally, we found devices through web searches.

Adilkhanov et al. [5] reviewed over 90 haptic feedback devices from 2010 to 2021, of which 26 were kinesthetic devices. We chose 21 devices for closer examination. Haptipedia [39] assessed 108 kinesthetic haptic feedback devices, focusing on those with a workspace exceeding $60cm \times 60cm \times 60cm$, identifying 12 devices. For haptic feedback gloves used in grabbing simulation, Pacchierotti et al. [35] analyzed 21 prototypes, with nine supporting haptic feedback for at least four fingers, meeting our inclusion criteria. In their systematic review from 2015 to 2021, Caeiro et al. [11] identified 24 smart gloves where only 10 offer tactile feedback and six provide kinesthetic feedback. The rest support only finger tracking. Additionally, we found 12 kinesthetic feedback devices through web searches.

In total, we found 60 devices, comprising haptic feedback gloves and other kinesthetic feedback devices. We evaluated these feedback devices based on our requirements by reading their papers or searching for content on their websites. The results of all devices and their fulfillment of requirements can be found in the supplemental material. However, Table 1 presents the list of the most promising haptic feedback devices, based on our requirements.

4.2 Final Choice

Out of all 60 devices, 30 are haptic feedback gloves, with 3 additionally containing kinesthetic feedback for the entire hand. These three devices are CyberForce, HIRO III [19], and FlyingPhantoms [8], which are grounded mechanical feedback arms equipped with a haptic feedback glove as an end-effector. While these devices could theoretically simulate grabbing, colliding, and weight sensations, their technical design limits their workspace. Therefore, the largest workspace they can cover is HIRO III with dimensions of $120cm \times 61cm \times 61cm$. Additionally, their complex design does not allow for the use of fewer feedback types, such as only collision and weight feedback. Hence, we do not further consider them. Consequently, we require at least a combination of two haptic feedback devices to cover our three haptic feedback types.

Grabbing Feedback Device We require a glove for simulating grabbing and identified 27 options. Only 13 meet our 15 N finger force requirement, with nine supporting at least four fingers. Two of these nine have a fixed grabbing pose, restricting variability. Among the remaining seven, three are commercial (Dexmo[3], SenseGlove Nova[4], HaptX Gloves G1), and four are research prototypes. Due to the complexity and limited replication information for research gloves, we chose one of the three commercial devices listed in Table 1.

The HaptX Gloves G1 provides kinesthetic feedback and numerous tactile actuators for a more realistic sensation. However, wearing the control system of the gloves on the back, which weighs about 8.5 kg, could influence the ergonomic pose and ergonomic investigation of the users, posing a potential problem. Therefore, we did not choose the HaptX Gloves. Both the Dexmo and the SenseGloves Nova are quite similar devices, with the SenseGloves Nova supporting only four fingers of feedback instead of five like the Dexmo, which still meets our requirements. In terms of cost, the SenseGloves Nova are much cheaper (4,500 USD) compared to the Dexmo (36,000 USD [11]). Additionally, we found studies where the SenseGloves Nova were successfully utilized [20]. Therefore, we decided to use the SenseGloves Nova for our haptic feedback system.

Collision Feedback Device Regarding the collision and weight feedback devices, we had to search for devices that do not have a predefined handle, as we need to wear a glove and should be able to

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[3] DextarRobotics. Dexmo Gloves. https://www.dextarobotics.com/

[4] Senseglove. SenseGlove Nova. https://www.senseglove.com/product/nova/

have free finger movement during the task. Therefore, out of the 30 remaining feedback devices, only 7 devices do not have a predefined handle and can cover the workspace we defined in our requirements.

Table 1 displays the remaining seven kinesthetic feedback devices we inspected more closely. First, we evaluated if one haptic feedback device can simulate weight and collision simultaneously, meaning we are looking for an active haptic feedback device with at least three degrees of freedom.

Here, we only found two devices, SPIDAR-W [34], and an electric muscle stimulation-based system (EMS) [32]. The EMS system uses electric muscle stimulation to simulate forces. Here, electrodes are attached to the users' bodies, triggering their muscles. The more muscles connected to electrodes, the more degrees of force feedback it can provide. Therefore, it would require most of the users' muscles to simulate weight and collision feedback. Additionally, the authors described their system as unrealistic for collisions. Therefore, we can only imagine it for weight simulation. The second device, SPIDAR-W [34], is a string-based haptic feedback device that connects a string to the user's hand and motors via a rig worn by the user on their back. Unfortunately, there is not much information about the total weight of the device. Still, we assume its weight would impact the user's ergonomic behavior, which is an important criterion during the VR task. Therefore, we do not consider SPIDAR-W further.

As both devices are unsuitable for weight and collision simulation, we have to combine two devices to simulate both feedback types. Therefore, we evaluated each device individually. For the collision devices, only STRIVE meets the remaining requirements, as the other devices (STROE [2], Windblaster [28], PropellerHand [4]) have too few degrees of freedom and too high latency. STRIVE [3] is a string-based haptic feedback device that can stop hand movement at collisions. Additionally, STRIVE's string-based design allows it to connect the system to the VR gloves via strings. As STRIVE also meets our other defined requirements, we decided on STRIVE as the collision feedback system. More details about STRIVE will be explained in the next section.

Weight Feedback Device Regarding the weight simulation device, potential haptic feedback devices include STROE [2], Drones [1], PropellerHand [4], Wind-Blaster [28], and the EMS system [32], each with its benefits and drawbacks, which we will briefly overview.

PropellerHand [4] and Wind-Blaster [28] are similar devices that use propellers for air propulsion to generate forces. Both devices attach to the user's hand and can simulate various forces, including weight. However, they both have the drawback of only generating forces downward unless users rotate their hands, which is required in our VR task. Therefore, we did not further consider them.

The drone system [1] operates by flying to the position where the collision with the user's hand occurs. As a result, the user feels the collision when the drone reaches its position. However, to simulate weight, the drone must push against the user's hand. If users move their hands quickly, the drone may struggle to follow them. Therefore, we did not choose drones for weight simulation.

STROE [2] is a string-based device worn as an extension attached to a shoe, which is then connected to the user's hand via a controllable string. The string, attached to a motor, generates force on the user's hand. One drawback of STROE is that the maximum force it can generate (7.2 N) is too weak compared to our defined requirements (40 N).

Considering all haptic feedback devices for weight simulation, none can provide enough force. Therefore, we chose STROE as the weight simulation device because its string-based design allows easy combination with a glove and the collision feedback device STRIVE. Additionally, unlike propeller-based devices, it allows users to rotate their hands. More information about STROE can be found in the next section.

4.3 Insights from Device Evaluation

During our device evaluation, we noticed that most haptic feedback devices (22 out of 30) have predefined handles, which means users have to hold the handle instead of being able to grab objects of different sizes. This design choice reduces realism and also prevents other devices from being combined. Therefore, we see a motivation for designing more haptic feedback devices with modular handles or attachment methods so that more feedback devices can, for example, be combined with haptic feedback gloves.

Additionally, during our device evaluation, we noticed that important specifications such as latency or precision are often not reported. For example, 21 out of 30 devices did not report latency, and 24 out of 30 devices did not report precision. However, this information is important to further consider devices for future research. Therefore, we recommend authors to report these specifications.

Regarding the replicability of non-string-based haptic prototypes, these devices are generally more challenging to replicate and especially difficult to combine. They often function as stand-alone products requiring specific end-effectors. In contrast, string-based haptic devices offer easier combination and integration possibilities [2, 3].

5 THE MULTI-TYPE HAPTIC FEEDBACK SYSTEM

Our haptic feedback system integrates three distinct haptic feedback devices (Figure 1 D) to give the user tactile sensations of grabbing, weight, and collision impact in a single hand. For the simulation of grabbing and interaction with virtual objects, we employ the commercially available SenseGlove Nova device (Figure 1 C), which was introduced in 2019. These gloves can exert up to 20 N force on each finger and deliver vibrotactile feedback through a voice coil actuator.

To simulate the sensation of weight, we utilize the string-based device STROE [2] (Figure 1 A). STROE is worn as an extension attached to a shoe, which is then connected to the user's hand via a controllable string. A motor applies force to the string to simulate the desired weight. With its rotatable rod and automatically movable pulley, STROE can generate downward forces independently of the user's hand position. While it can simulate weights up to 720 g, lower than our defined requirement, we found that the limitations of other weight simulation devices outweighed this drawback. As STROE operates based on strings, we can attach its string to the bottom of the SenseGlove. Additionally, since STROE is attached to the user's foot, its operational range is only restricted by the Bluetooth range, that is, approximately 25 meters.

For simulating collisions with the hand, we employ the haptic feedback system STRIVE (Figure 1 B). STRIVE consists of multiple small string-based haptic feedback devices that simulate collision by halting the extraction of the attached strings connected to the user's body. The strings can be extracted up to 2 meters. The STRIVE setup offers great flexibility, allowing the placement of STRIVE devices in various locations and connection to different body parts or tools. To simulate a collision from above, the two STRIVE devices will be activated, while STROE will not be used for this purpose. As a result, STROE serves as the sole connection between the users' foot and their dominant hand. Similar to STROE, we attach the strings of STRIVE to the SenseGlove. However, it's worth noting that STRIVE devices are fixed to the physical environment, which restricts user movement to a confined area of approximately $2m \times 2m \times 2m$ in our setup. User body rotations are also limited to around 90 degrees in both directions to prevent entanglement of the strings.

We have designed the overall system to be modular, enabling any combination of two of the three devices. Previous research [36] has shown benefits in specific scenarios when using only one type of feedback, reducing complexity when unnecessary. It is also possible to utilize each device individually. However, since existing evaluations of each device exist, we did not consider employing just one device in our system. Instead, we focused on combinations such as STRIVE and the SenseGlove, STROE and the SenseGlove, and STROE and STRIVE. In the last combination, an interaction device is still required. For this purpose, we employed a state-of-the-art VR controller, the HTC Vive controller. We combined all the components by connecting the strings from STRIVE and STROE to either the SenseGlove or the VR controller. Henceforth, we will refer to the SenseGlove as the *grabbing* simulation device, STRIVE as the *collision* simulation device, and STROE as the *weight* simulation device.

The total cost of the entire haptic feedback system is approximately 4750 USD (STROE 150 USD + STRIVE 4 × 25 USD + SenseGloves

4500 USD) plus the VR System about 6800 USD (HTC Vive, Controllers, Base Stations 1500 USD + HTC Vive Trackers 2 × 150 USD + 5000 USD Workstation).

Technical and Software Implementation As the original STROE, STRIVE, and SenseGloves use Bluetooth Classic communication, we often encountered problems connecting them all to our computers. Bluetooth Classic has limitations when connecting multiple devices simultaneously. Therefore, we integrated Bluetooth Low Energy into the four STRIVEs we used to solve the problem.

The system is implemented in Unity, and each device mostly works independently of the others. For the SenseGloves, we utilize the implementation of the SenseGlove developer kit, which stops finger movement after grabbing an object, depending on the variables assigned to that object, such as stiffness. We extended this grabbing function to control STROE regarding the weight of the grabbed object, following the implementation provided by the developers Achberger et al. [2]. STROE is activated after the user grabs an object, depending on the mass value assigned to it.

For STRIVE, we utilized the collision system of Unity. When a collision occurs between the grabbed object and other virtual objects, we stop hand movement by activating the responsible STRIVE, which has an angle of less than 90 degrees between the collision direction and the string, based on the method developed by Achberger et al. [3].

The current system uses the HTC Vive Base Station[5] to track devices like the HMD, STROE, and SenseGloves. Consequently, a standalone VR system that uses inside-out tracking, such as the Meta Quest 3[6], would not be compatible, as it cannot track these devices. However, this limitation could be addressed in future developments.

6 PILOT STUDY

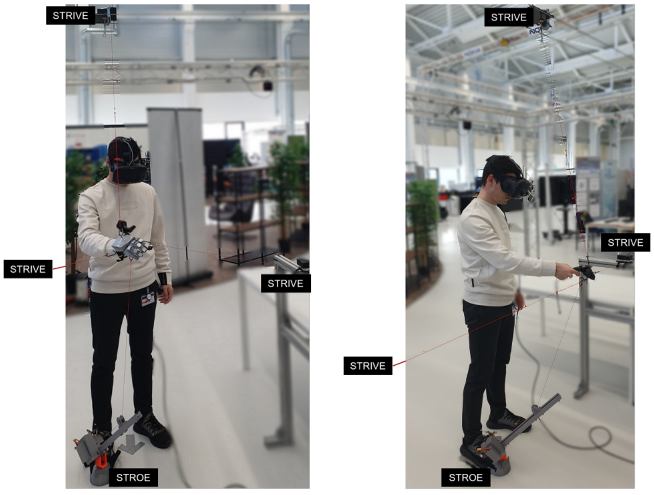
Before conducting the expert study, we conducted a pilot study to validate and refine our haptic feedback system, serving as a proof-of-concept and identifying areas for potential improvement. Four employees from our department (2 m, 2f, age between 25 - 27) participated in the pilot study, providing valuable feedback that encompassed both positive and negative aspects. Two out of the four participants had prior experience with haptic devices, and all had VR experience ranging from 2 to 4 years. These participants were involved only in the pilot study and did not participate in the subsequent expert study. We utilized this feedback to make necessary enhancements and adjustments to ensure a smooth execution of the subsequent expert study. In the following section, we outline the setup of the pilot study, which mirrors the setup of the expert study.

6.1 Study Setup

In our setup, we arranged three STRIVEs in a triangular configuration, with one module positioned above the user's head and two on the left and right sides. To ensure stability, we securely mounted these modules on an aluminum profile. The distance between the left and right collision feedback devices was approximately 1.5 meters, with a mounting height of around 1.20 meters, and the STRIVE above the user was on a height of 2.5 meters. We observed no influence between device positions and user height, so the system remained consistent for all users. This configuration provided a working space of roughly $1.5m \times 1.5m \times 1.5m$, allowing sufficient movement during the tasks.

For right-handed participants, we attached the weight simulation device to their right foot, and for left-handed participants, to their left foot. We then connected the strings of the collision and weight simulation devices to the carabiners on either the grabbing feedback device or the VR controller.

We used the HTC Vive Pro as the VR headset. Participant tasks, detailed in Section 3, were developed and implemented in Unity, as shown in Figure2.



(a) (b)

Fig. 3: Setup of the expert study. Left: The setup with SenseGlove, STROE and STRIVE. Right: The setup with an HTC Vive Controller, STROE, and STRIVE.

6.2 Results

Participants struggled with the *grabbing* device when grasping small objects, like screws, due to limited finger tracking accuracy. They performed better using a tweezer-like motion. Participants also needed time to get used to the device. To address this, we added a short training session at the start of the study to teach them optimal techniques for grasping small objects.

Two of the four participants reported that the strings from the *collision* and *weight* devices restricted their hand movements. Specifically, they struggled with the *collision* device, as the carabiner slipped between their thumb and index finger when grasping objects. To address this, we developed customized attachment points for each string based on its direction, moving away from a single attachment position. Figure 1 B shows these new attachment options.

Another issue highlighted by the participants was the performance of the software simulation. The imported models of the car parts had complex underlying meshes, resulting in a high number of vertices involved in collision calculations. This complexity led to a low frame rate and significant latency in the haptic feedback devices. Consequently, participants could penetrate virtual objects with other objects because the *collision* device halted the interaction too late. To address this problem, we remodeled all tangible objects and other chassis parts using primitive shapes such as boxes, spheres, and cylinders. We tried to ensure the precision of the remodeled objects, thereby enhancing the overall accuracy of the simulation.

7 EXPERT STUDY

We conducted a user study involving experts from the automotive industry who regularly utilize VR in their work. The primary objective of this expert study was to evaluate the advantages, disadvantages, and technical limitations of our multi-type haptic feedback system in the context of a real automotive use case. Additionally, we aimed to determine which setup combinations yield the greatest benefits in performing the assigned tasks, considering that utilizing all three haptic feedback devices simultaneously could potentially introduce complexities in specific scenarios. We used the same setup and tasks as those used in the pilot study, including the improvements implemented based on the insights gained from the pilot study.

7.1 Participants

We conducted a study involving 12 (10 m, 2 f) automotive VR experts. The main goal of our study was to test the approaches with participants

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[5] HTC Vive, 2024. https://www.vive.com/de/accessory/base-station2/

[6] Meta Quest 3, https://www.meta.com/de/quest/quest-3/

Gender	Age	Years in VR	Frequency of VR Usage	Haptic Experience
Male	38-50 years	>10 years	several times daily	Strive
Male	38-50 years	1-4 years	several times daily	Strive
Male	25-37 years	1-4 years	several times daily	Strive
Female	51-60 years	>10 years	2-5 times per week	Strive, Manus VR
Male	25-37 years	1-4 years	<1 time per month	Strive, Manus VR
Male	51-60 years	>10 years	1 time per week	Strive, Manus VR
Male	< 25 years	1-4 years	1 time per week	Strive
Female	25-37 years	1-4 years	1 time per month	Strive
Male	51-60 years	>10 years	1 time per week	Strive
Male	25-37 years	1-4 years	several times daily	Strive, Stroe
Male	25-37 years	<1 year	2-5 times per week	
Male	25-37 years	1-4 years	several times daily	Strive, Manus VR

Table 2: Automotive VR expert data which participated in our user study.

with considerable previous VR experience in the respective automotive application domain. Experts give different answers compared to novices, especially when focused on qualitative feedback [27, 33]. We asked the participants about their age, working experience with VR, frequency of VR usage, and previous experience with haptic feedback devices. The results can be seen in Table 2.

7.2 Procedure

In total, we had four conditions: *Weight* (**Wei**) + *Grabbing* (**Grab**) + *Collision* (**Col**) (Figure 3 (a)), **Wei + Grab**, **Wei + Col** (Figure 3 (b)), and **Grab + Col**. We did not evaluate only one device, as there are already evaluations about the devices and their benefits.

We used a within-subject design for the user study so each participant could experience all four combinations of haptic feedback devices. To minimize learning effects, we employed a Latin square to randomize the order of conditions for each participant. Two researchers conducted semi-structured interviews, took detailed manual notes due to recording restrictions, and later coded them for analysis. At the beginning of the study, we displayed the Unity scene on a desktop and explained which car parts needed replacing. Each participant spent approximately 60 minutes on the study.

In the study, we primarily focused on qualitative feedback, rather than quantitative. Quantitative measures, such as task performance, are often too limited for early exploratory studies such as ours [24]. We expect that haptic feedback conditions will even lower the quantitative task performance measures as tasks become more realistic and, as such, harder to conduct. For instance, if the task is to assemble a car component, the heavier the car component is the more realistic but also the more challenging the task. Thus, the task performance would decrease. The main purpose is to simulate in VR how hard these tasks are in reality; the goal is not to make the VR experience as easy and fast as possible. Therefore, we based our questions on *Defining Haptic Experience* [30], which guides the design and research of haptic systems. We did not fully query the questionnaire, as some questions were redundant. We asked about **intensity** (the overall perceived strength of feedback), **timbre** (overall tone, texture, color, or quality of the feedback), **utility** (the ability of haptics to benefit user experience), **causality** (how easily a user can relate haptic feedback to the source of interaction), **consistency** (ability to provide reliable haptic feedback), **saliency** (noticeability of the haptic feedback as it relates to its purpose), **harmony** (how well the haptic impressions fit together), **immersion**, and **realism**. We made notes of their answers. Additionally, they had to answer each question on a 7-point Likert scale, where 7 was the most positive result, and 1 was the most negative.

At the end of the study, we asked for their positive or negative impressions, suggestions for improvement, which haptic feedback was individually most important for completing the tasks, and which combination of devices seemed to make the most practical use. These questions were related to the current state of the devices. Additionally, we asked the participants to imagine the same setup but with no technical device limitations or problems. We asked them again which combination and device would have the highest benefit. These speculative study questions can inspire new design ideas, concepts, and directions and are common in the human-computer interaction community [44]. By envisioning future scenarios, designers can push the boundaries of what is possible, explore unconventional interactions, and think creatively about user experiences that may not exist yet. We included these speculative questions to mitigate bias from technical limitations and assess their impact on the participants' perceptions.

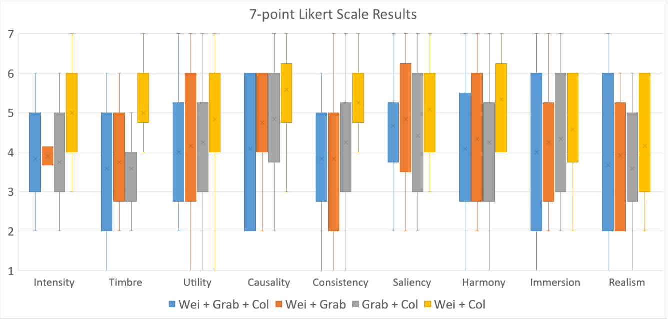

Fig. 4: The average values on the 7-point Likert scale for the haptic questions.

Our results are based on an exploratory proof-of-concept study and mainly focused on the experts' qualitative feedback. Qualitative analysis is common in the human-computer interaction (HCI) community [31], which desires to gain an in-depth understanding, contextualize user behavior, explore new phenomena, and maintain a human-centered approach. By harnessing the power of qualitative research methods, HCI researchers seek to uncover valuable insights that inform the development of user-centric technologies and enhance the overall user experience. We used an estimation-based approach with effect sizes and confidence intervals for the quantitative survey data to interpret our results. Statistical analysis practices recommend this approach [7], which overcomes several limitations and biases of classical null hypothesis testing with p-values (NHST) [16, 18]. Cumming and Finch guide how p-values can be estimated from 95% CI plots [17].

7.3 Results and Discussion

The results were divided into two categories: haptic questions and additional questions. Given that our study was exploratory, our primary emphasis was on gathering qualitative feedback in cross-relation to the results of the questionnaires.

7.3.1 Haptic Questions

Figure 4 presents the results of the average 7-point Likert scale answers for each condition. The average values for each question in each condition are as follows: 5.0 (SD: 0.38) for **Wei + Col**, 4.1 (SD: 0.37) for **Grab + Col**, 4.2 (SD: 0.35) for **Wei + Grab**, and 4.0 (SD: 0.28) for **Wei + Grab + Col**. Notably, the condition **Wei + Col** performed the best in each haptic question. In the following, we will list our major findings, mostly based on the qualitative feedback of the experts.

The grabbing device caused issues, particularly when handling small objects. The experts highlighted problems related to grasping, which impacted all haptic-related aspects we inquired about. The **Wei + Col** condition that does not involve the grabbing device received ratings of 0.8 to 1.0 higher than the others.

Of the 12 experts, 10 criticized grabbing in various conditions requiring grasping. Regarding realism, four participants in the **Wei + Grab** condition criticized the feedback associated with grabbing, as it compromised the sense of realism. Regarding the question related to timbre, one participant explained, *"It was very difficult to grasp screws but easier with larger objects."* However, in the **Grab + Col** condition, two participants mentioned that they perceived haptic feedback as unnecessary when dealing with larger objects since *"the spatial impression was already well-established."* Participants expressed that compared to the condition without grabbing, the intensity was *"much more pleasant because the strong influence of grabbing was not present."*

Additionally, some participants shared their experiences with the controller and stated that when *"the focus was not on grabbing, the* *immersion was higher, although it felt more technical, making it less immersive but more practical."* Other participants compared the usefulness of grabbing with other haptic feedback sensations and mentioned that *"the more frequently grabbing was used, the more evident it became that it was not as useful, and that weight was more important."* However, we also received positive feedback about grabbing, where two participants noted the absence of grabbing, expressing that *"at times, adjusting the grip on other objects added to the realism."*

The main issue with the grabbing feedback device was the mismatch between the expert's finger pose and the virtual finger pose. This discrepancy caused discomfort, making the feedback more distracting than beneficial. Chen et al. [12] surveyed hand pose estimation techniques, including wearable sensors and computer vision-based methods. They encountered challenges with data gloves and wearable sensors, especially with variations in user hand sizes. Computer vision-based tracking shows promise but struggles with occlusion and when hands are outside the camera's view. One potential improvement could be combining both methods to improve accuracy.

Simultaneous usage of all feedback types was often assessed as excessive. When we combined all feedback types, most experts agreed that there were *"too many impressions at once."* We observed that there were various reasons behind this sentiment.

One negative aspect mentioned by the experts was that they described the setup as *"too distracting and restrictive."* One participant suggested that *"reduced individual feedback would be better."* Two of the three haptic feedback devices were string-based, resulting in four strings when using them together. In the **Wei + Grab + Col**, this was considered to restrict the necessary movements partially. Interestingly, however, the **Wei + Col** condition, which also utilized four strings, was rated as the best feedback combination. This fact might indicate that the strings alone might not be the main problem. Instead, the additional effort required for grasping feedback might have resulted in mental overload, making them feel restricted and distracted.

Another negative aspect mentioned by the experts was the setup effort. Some experts explained that this combination is *"theoretically super useful in the ideal case, but in the current case, it required too much effort to get it almost right."* This statement surprised us, as it took only a few seconds to connect the strings to the controller or SenseGloves. We agree that the setup may appear complicated with its four strings. During the study, we connected the strings ourselves to the user. We can imagine that if we let participants connect the strings themselves, they would describe the setup as simpler because its complexity is mostly visual and not in its usage.

Regarding the causality questions, the experts had difficulty identifying the source of haptic feedback due to the multitude of impressions and the need to evaluate each feedback type individually, which was challenging due to the combined feedback's confusing nature.

Weight and collision feedback in combination yielded the best results across all haptic dimensions. Regarding the results obtained from the 7-point Likert scale, the average values of the **Wei + Col** condition were consistently the highest for each haptic question. When considering the qualitative feedback from participants, it becomes clear that the absence of grabbing feedback was not the sole reason for the positive feedback in the **Wei + Col** condition.

Many participants stated that the haptic feedback *"complemented each other very well,"* and nine participants expressed that this form of multi-type haptic feedback felt useful. This feedback was not deemed device-specific but should also be applicable to other devices capable of simulating weight and collision, such as the Inca 6D [37] and the Virtuose 6D [22], both of which are commonly used in the industry. One participant provided further insight into the benefits of collision and weight simulation in the VR task, explaining that *"the direction can be estimated, and the weight force gives an impression of realistic holding while still allowing free movement in the hand."* Regarding the causality question, six participants in the **Wei + Col** condition reported reliably identifying the source.

Interestingly, four participants criticized the realism in the **Wei + Col** condition due to the absence of grabbing feedback. However, we observed in other conditions that grabbing feedback reduced realism, emphasizing the importance of the feedback type and indicating that it is not yet adequately simulated.

The combination of haptic feedback devices with continuous and abrupt feedback was perceived negatively. Our weight simulation feedback device continuously applies forces to users when they hold objects, allowing for different levels of force strength. On the other hand, the collision device only provides abrupt impact feedback, which participants referred to as on/off feedback.

During our study, we observed that participants criticized this interaction characteristic between the two different approaches. Three participants faced difficulties due to the distinct nature of the feedback devices, as indicated by the comment: *"very different in that one is continuous, and one is collision on/off."*

As a result, the harmony of the **Wei** and **Col** combination was criticized, and the combination of **Wei** and **Grab** was preferred in terms of harmony because *"the two feedback types go well together as they do not have on/off forces but provide a consistent feeling."*

Regarding causality, some participants noted that the **Wei + Col** condition was slightly more distinguishable than **Wei + Grab + Col** because the overall impression was lower. However, individually, the devices felt more intense due to their continuous and abrupt feedback types. Nevertheless, the **Wei + Col** condition was still rated as the best. Although participants criticized the difference between continuous and abrupt feedback types, they still recognized more benefits in this condition than the others. We believe this issue also affects other devices as well. However, it could be reduced by switching the collision actuator to an active actuator, such as the Inca 6D [37], which can simulate damping or spring characteristics.

Weight simulation was perceived different among conditions Participants perceived varying levels of weight simulation across conditions. In the **Wei + Grab** condition, three participants found the weight simulation intensity too weak, despite the objects' weight remaining consistent across all conditions.

In the **Wei + Col** condition, where participants used a controller linked to the weight feedback device, some perceived the objects as heavier compared to other conditions.

One possible reason for this behavior could be the different attachment points of the weight simulation device to the user's hand or controller. One participant suggested that *"the weight of the controller may be applied too far forward, causing it to tip over."* We believe this variation in attachment points could influence the participants' perceptions of weight simulation.

7.3.2 Additional Questions

Regarding our additional questions, we collected further major findings:

Collision feedback is perceived as the most important and useful feedback type in our current setup. We first addressed whether the experts would use the haptic feedback system in their daily work. Of the 12 participants, nine stated that they would utilize collision feedback, while four experts would also opt for weight simulation in certain special use cases. However, it was noted that weight simulation is only applicable in specific and less frequent scenarios, as expressed in the following quote: *"It depends on the use case. For accessibility and general tasks, collision and controller feedback are sufficient. For achieving realism, weight simulation becomes important."*

We also inquired which device assisted participants in their tasks most. Every participant agreed that collision feedback offered the highest benefit. They mentioned that collision feedback enhanced their spatial perception and gave them a better understanding of the component, stating: *"I get an impression of the component and more information about what I am actually doing."*

We also believe this result can be generalized to other VR domains. For example, in medicine, force feedback is used to simulate the texture of tissues and organs [46]. In the gaming domain, tactile feedback suits like the TeslaSuit[7] are already in use. We believe our system could be

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[7] VR Electronics Ltd. TeslaSuit. https://teslasuit.io/products/teslasuit-4/

useful here too, as most objects a user touches, like furniture, walls, or doors, are generally solid.

The importance and usefulness of grabbing feedback are influenced by technical limitations. We revisited the question of which haptic feedback types experts would use if there were no technical limitations. All 12 participants chose collision feedback. Nine also favored adding weight and grabbing feedback, differing from their previous choices. When asked which feedback type was most helpful without limitations, six participants prioritized collision feedback, five preferred grabbing feedback, and one favored weight feedback, showing differing results compared to previous choices.

The findings indicate that grabbing feedback emerged as one of the most important types of feedback without technical limitations. However, it is worth noting that our grabbing device, SenseGlove, currently stands as one of the leading commercial devices, with few alternatives offering kinesthetic feedback [11]. Weise et al. highlighted interaction challenges with small objects [43]. They proposed alternative interaction techniques to address these hardware limitations, such as raycasting methods like HOMER [10]. We believe these techniques could be particularly effective for interacting with smaller objects.

The fast and easy setup of the system was a major positive aspect. When we asked the experts about the positive aspects of the haptic feedback system, four participants emphasized the fast and easy setup of the system. While the experts did not change the setup between each condition themselves, they observed us making the necessary adjustments. On average, the setup change took less than one minute, as we only had to attach the strings of the devices accordingly. This quick and simple setup process was in stark contrast to feedback devices like exoskeletons [21] or other wearable feedback devices [6,34,35]. However, some experts found that setting up all three feedback types required more effort compared to combining just two types.

This result was also reported in other haptic feedback systems for the industry domain [3], highlighting that a fast and easy setup is one of the most important requirements of a haptic feedback device in the industry. However, we believe this requirement is less important for other domains such as gaming, as users often spend multiple hours in one VR session instead of only a few minutes like in the industry.

Decide own trade-off between technical limitations and benefits is important. The final question aimed to find the most useful combination of haptic feedback devices. Nine participants agreed that collision and weight feedback were the most important. Two perceived all three feedback devices as crucial, while one favored collision and grab feedback.

When asked the same question without technical limitations, the responses varied. In this case, 10 participants indicated that combining all three devices would be the most useful. One participant explained that they would exclusively use the system for advanced VR workers, as they mentioned that *"inexperienced people tend to have an 'aha' experience with VR and then engage in unwanted actions like walking around the car, which is not possible with this system."* Two participants rated the combination of collision and weight feedback as the best choice without technical limitations.

Obviously, the more haptic feedback types available without technical limitations, the better. However, it is important to note that technical limitations currently constrain our haptic feedback devices and others. Huang et al. [26] provided examples of devices that combine multiple haptic feedback stimuli, which offer both advantages and disadvantages. They have drawbacks, such as reduced comfort and mobility, as well as increased size and weight. Therefore, employing a flexible multi-type feedback system proves advantageous, as users can choose the specific haptic feedback modalities based on their respective limitations. Users must consider the *"relationship between effort and benefits,"* a point emphasized by one of the participants, which may vary depending on the specific use case.

Therefore, we believe our flexible feedback system could be applicable in the automotive industry and other domains like gaming. While some games involving extensive movement and object interaction may not fully utilize all three devices, the weight and grabbing simulation device, or their combination, could still be effective. Additionally, scenarios such as surgery simulations, where users often stay in a fixed position, could benefit from the entire system.

8 LIMITATIONS

During our study, we encountered different limitations. First, our study only focused on a one-handed use case, which could pose challenges for tasks requiring bi-manual interaction. The strings of the collision and weight simulation device could become entangled in such scenarios. This limitation should be considered when extrapolating our findings to bi-manual tasks.

Another technical limitation of our system is limited mobility. Participants were restricted to walking within a confined area measuring approximately $1.5m \times 1.5m$. Moreover, complete body rotations were constrained due to the string-based technology. However, it is important to acknowledge that movement is predefined in most automotive use cases and requires less variation in different directions.

It is important to highlight that our investigation primarily focused on the devices' hardware, neglecting the software aspect of combining feedback devices. We believe most of the devices can be combined in their software, but detailed information about the code is often lacking.

Additionally, most participants had prior experience with the collision simulation device STRIVE, potentially introducing bias. However, we do not believe this experience influenced our results, as the STRIVE device does not have a training or learning effect.

Our study is a qualitative expert study. We deliberately did not include novices as we were interested in the devices' performance in a professional work setup. An expert study allowed us to ensure a high degree of ecological validity. The downside of expert studies, however, is that they often come with a limited diversity that is inherently tied to the distribution of the underlying expert population. Expert studies also tend to have smaller sample sizes due to the challenging recruiting process [41]. However, smaller sample sizes are common in expert studies, specifically if they are primarily qualitative such as our study [27,33].

9 CONCLUSION AND FUTURE WORK

Our research aimed to create a multi-type haptic feedback system tailored for automotive VR tasks, integrating weight, grabbing, and collision sensations simultaneously. We selected devices carefully to ensure they were optimal for our study.

We conducted two user studies to gather feedback and refine our concept. The pilot study aimed to fine-tune the haptic setup and validate our approach. Building on these findings, the second study involved twelve automotive VR experts. It aimed to identify practical limitations and determine which combinations of haptic feedback provided the greatest benefits for automotive VR tasks.

Our study results indicated a clear preference for combining weight and collision feedback due to technical limitations with the grabbing device. However, participants recognized the importance of grabbing feedback without such limitations. These findings underscore the need to overcome technical constraints to enhance the haptic experience.

Our future plans include developing a software tool to assist users in selecting an optimal multi-type haptic setup. This tool will utilize collision data from tasks performed without haptic feedback to help users identify which feedback types offer the most benefits. Users can then balance effort and benefit in their haptic feedback preferences. Additionally, we aim to integrate our multi-type haptic feedback device with an omnidirectional treadmill. This integration aims to decrease movement restrictions observed in our study. Through this extension, we want to test our system in new VR domains, particularly in interactive games that demand extensive movement.

ACKNOWLEDGMENTS

Funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2075 – 390740016. We acknowledge the support by the Stuttgart Center for Simulation Science (SimTech) and Katherine J. Kuchenbecker for her valuable support.

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